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Net-zero energy design and energy sharing potential of Retail - Greenhouse complex

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ABSTRACT

The global projection of urban growth and increasing population densification creates new opportunities for an expanded role of greenhouse technology. Coupling a greenhouse with supermarket, as a method for energy sharing, has been identified as a promising method to increasing efficiency of the building operations while reducing dependency on transportation. This paper presents the results of a simulation study of an urban centric greenhouse-retail complex and explores optimal building design parameters, integrating renewable energy technologies and exploring energy sharing strategies within both buildings of the complex. The results show that with an integrated building design approach, cutting edge technologies and high energy efficiency measures a net reduction of 27% energy in the greenhouse-retail complex is achieved compared to design complying with the minimum requirement of the applicable energy codes. Additionally, by sharing waste heat recovered from retail refrigeration compressor racks, 21% of space and ventilation heating demand of the greenhouse and energy demand for irrigation water and service hot water for the complex can be met. Employing on-site renewable energy generation, net-zero energy performance of the greenhouse-retail complex can be achieved. It has been found that by feasible combination of buildings optimized to harness on-site energy and sharing energy between the individual buildings, dependence on utility grids can be reduced, in addition to having a local source of food growth for climate change resilient urban infrastructure.

1. Introduction and background

World's cities contribute 70% of global greenhouse gas emissions while occupying only 2% of the world's land surface [1]. Major building types contributing to global greenhouse gas emissions (GHG) in urban built environment include commercial (28%) and residential buildings (29%) [1,2].

Retail sector is considered one of the highest energy intensity in the commercial buildings. This high energy intensity is due to large heating and cooling loads as well as reliance on inefficient refrigeration units [3]. In fact, food retail amenities consume nearly half of the electrical energy of the entire building in refrigeration [4–6]. Several research studies have explored the development of lower energy consuming supermarkets. A guide developed by American Society of Heating, Ventilation & Air-conditioning (ASHRAE) provides design recommendations to achieve reduced energy consumption of big retail buildings [7]. This guide provides green design features for optimized envelope, lighting power density, mechanical systems and water conservation. Similarly, Doty [4] provides comprehensive recommendations for energy conservation and design optimization for retail buildings to reduce their energy footprint.

Since refrigeration makes up the majority of energy end-use in supermarkets, optimizing the design and operation of retail refrigeration system offers potential of energy usage reduction in the food retail buildings. Several studies have explored energy efficiency improvement for retail refrigeration systems. Nall [6] outlines means for recovering waste energy from refrigeration compressor cycle to produce low-grade heat to reduce retail heating load. Similarly, Miena [8] explores viability of vapour-absorption refrigeration system to reuse the waste heat to provide cooling for refrigerated cases. Some studies have explored optimization of refrigeration systems like reducing infiltration into the refrigerated cases, reducing electrical loads and power factor corrections to reduce energy usage of refrigeration systems [5,9].

Another energy intensive aspect of urban infrastructure is food production, food processing and transportation of agricultural products and produce. IPCC [10] estimates that the environmental impact of food systems contribute approximately 24% of the global GHG emissions. It is estimated that the average distance that North American produce travels, from source to point of sale is about 2000 km [63]. Based on a typical household food requirement, food transportation is

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responsible for approximately 11% of the total GHG emissions associated with food production in the US [11]. Current urbanization projections can create opportunities for mitigation of resource consumption coupled with sustainable local food production.

Greenhouses are commonly used to adapt the environment to the needs of the crop production, and as a means to control the food production locally and as a safeguard against the circumstances of food insecurity such as lack of basic food needs, shortage of arable land, harsh climate and geographical remoteness. In context of urban infrastructure, building integrated or roof top greenhouses have been investigated for different geographical locations [12]. Sayne-Mengual [13] has investigated rooftop greenhouses (RTG) in Barcelona while accounting for the agricultural crop growth and transportation. This study shows that RTG has 42% less environmental impact compared to multi-tunnel greenhouse system and is 21% cheaper to produce the crop yield. Combining an urban centric greenhouse to commercial retail sector can provide a number of energy and environmental benefits, including serving as a protective buffer from the elements to reduce the building's heating energy demand [14].

Energy sharing between individual buildings in a cluster of buildings can be a viable solution to reduce energy footprint of a community. For example [15], explore building energy system optimization by utilizing waste heat from cogeneration by means of genetic algorithm. This study shows that with an appropriate combination of heating plants and operation optimization, distributed energy systems based on cogeneration offer significant potential to save energy. This energy saving is achieved due to effective utilization of waste heat from power generators. Chung et al. [16] explores energy sharing system optimization of a combined heat and power (CHP) plant applied to a mixture of buildings comprising of residential, offices, hospitals, retail and schools. Chung et al. [16] shows that with optimal selection of building types and proper system size selection, energy sharing between an energy community is a viable option when using CHP system. Kayo et al. [17] concludes that for an energy community comprising of an office building, hotel, hospital and a retail center, a CHP plant with energy sharing within the energy cluster has advantages of energy management within the boundary compared to treating buildings as separate cases. Kayo and Ooka [18,19] have explored energy sharing between an office and apartment building and have shown significant reduction in energy consumption of the cluster by using waste heat from the office building. However, most of energy sharing research available is either focusing on CHP type of systems or has not explored any case study for an urban centric greenhouse attached to a retail amenity.

Additionally, life cycle cost and environmental impact can be used as supporting tools in the design of buildings, to significantly reduce the total energy and GHG emissions over the life of the building (Dwaikat et al. [20,21], and Mehdi et al. [22]). Cabeza et al. [23] has shown that life cycle energy and cost analyses play crucial role in any construction project, including traditional buildings. Cellura et al. [24] has developed a tool to co-simulate life cycle assessment along with energy and environmental payback times. Although this aspect is not studied in the current paper, introducing such study can provide a more holistic understanding of the environmental impact of various technologies and design strategies implemented.

This paper addresses the gap in existing research concerning design options of retail and greenhouses and demonstrates innovative approach to share energy between these two building types. This paper explores optimal design parameters of various building systems including energy, mechanical, lighting, and process refrigeration. In addition, optimal operations of heating plant, cooling plant, control system, waste heat recovery have been investigated. Surplus waste heat from retail refrigeration compressor racks has been shared with the greenhouse, thus reducing primary energy consumption of the greenhouse in particular and the overall building complex in general. On-site renewable energy generation has been modelled for net-zero energy design.

2. Methodology

The current study aims at developing a prototypical model for progressively climate change resilient urban-centric food retail amenity with attached indoor climate controlled agricultural center or greenhouse. Calgary, Canada (51°N) is chosen for this study. This climatic zone represents long and harsh winters, with short agricultural season and dense urban-centric infrastructure.

The retail-greenhouse complex has been optimized using innovative research in energy systems and on-site renewable energy generation. This study also explores the potential of energy sharing between the individual buildings of the complex to reduce dependence on utility grid in addition to having a local and reliable food source for climate change resilient urban infrastructure.

This study is divided into five main parts, as summarized below.

1. The first part aims at developing a reference or base-case model for a typical retail block. The geometry, architectural, mechanical and electrical design inputs for the retail model are based on the statistical prominence and governing building and sustainability codes for the site.
2. The second stage aims at developing a greenhouse model integrated to the retail. The objective is to assess the viability of urban centric agricultural growth center, integrated to a retail amenity.
3. The third stage comprises a detailed parametric approach used to determine design criteria for the greenhouse and retail complex to maximize energy efficiency. This parametric analysis is carried out to optimize the HVAC system for the greenhouse-retail complex with the use of energy efficiency technologies.
4. The fourth part investigates the retail-greenhouse complex to generate on-site electricity by employing photovoltaic panels.
5. The last part of the study focuses on exploring waste heat recovery and sharing surplus heat between the retail and greenhouse to reduce dependence on utility grid.

3. Development of code compliant greenhouse retail complex model

The details of retail-greenhouse complex (Complex hereafter) are presented in the sections below:

3.1. Retail and greenhouse geometry and envelope parameters

The baseline model is developed using a number of codes and standards including the Alberta Building Code [25,26] and the National Energy Code for Buildings [27]. These codes are mandated by law for all buildings at the project site. The base model serves as a reference in a comparative study in which specific building envelope, mechanical, electrical and site heat recovery systems are systematically modified to achieve optimal energy performance. The Complex comprises of sales area, backroom and cold-room in addition to a greenhouse.

The retail assumes a basic geometric rectangular design of 45 m × 45 m plan dimensions and 4.3 m height. The refrigeration system is divided into low temperature (frozen displays and walk-in freezers) and medium temperature (dairy, produce, meat etc.) configurations, each supplied by its own compressor racks. Overall window area for the retail has been modelled at 0% and the lighting has been modelled at 8 W/m^2. Insulation for the retail has been modelled at 3.3 m^{2}K/W for the exterior walls and 5 m^{2}K/W for the roof as per the optimization done by MacGregor [3,28].

A cold-room of dimensions of 30 m × 10 m x 4.3 m within the retail area has been modelled. The coldroom houses all medium range temperature displays. Defining medium range refrigeration into a separate coldroom zone has shown a decrease in the retail area electrical load by 11% [3]. The temperature of the coldroom is maintained between 2 and 5 °C. In order to reduce merchandizing concerns and for the customers

to see the available produce [29], a double glazed clear pane assembly is used as a boundary wall.

Greenhouse is added to the south side of the retail. The greenhouse dimensions are 45 m × 10 m x 1.3 m (slanted to retail at 4.3 m). The greenhouse with all glass construction receives a significant amount of solar heat gain and hence the boundary between the greenhouse and the retail is insulated to reduce heat transfer between the greenhouse and the supermarket. An optimized value of 3.3 m^2K/W has been assumed for the greenhouse-retail boundary. Increasing the insulation value beyond this point shows that the thermal loads and the energy performance of the Complex changes only marginally by < 1% [3].

Greenhouse windows are assumed to be triple glazed, low-e, low solar heat gain coefficient and argon filled. This window configuration reduces the solar thermal load in the Complex by 80% compared to using a single glazed assembly for the greenhouse [3]. In addition, movable shades and insulation have been modelled for the greenhouse to reduce heat loss to outside ([30,61,62]). A rolling shade with 25% solar transmittance shows a reduction in cooling loads by 70%, and an overall reduction in energy consumption by 26% for the greenhouse [3]. Lighting for the greenhouse has been assumed to be 22 W/m^2. The key design parameters are presented in Table 1.

Fig. 1 below shows geometry of greenhouse-retail complex as modelled for this study.

3.2. Energy modelling and simulation tool

EnergyPlus is used for modelling and simulation for this analysis. EnergyPlus is a whole building energy simulation program used to model both energy consumption for heating, cooling, ventilation, lighting and plug and process loads and water use in buildings [31].

In order to get high resolution control for estimating the surface heat transfer coefficients and using advanced dynamic selection of the convection models based on the space conditions defined in the model, EnergyPlus surface convection algorithm is chosen to be 'Adaptive'. Adaptive convection algorithm organizes a large number of different convection models and automatically selects the one that best applies [31].

Similarly, to compute the surface heat fluxes more accurately, the 'Conduction Transfer Function' algorithm has been used. Simulation time step of one per hour is used.

The weather file used in the simulation is based on the data for Calgary, Canada as published by the American Society for Heating Ventilation & Air-Conditioning (ASHRAE) Handbook, HVAC Fundamentals [32].

3.2.1. Schedules

Building operating and occupancy schedules have a large impact on the overall energy usage, energy profile and energy cost. The operating schedules of the Complex in EnergyPlus are specified as per the ASHRAE Standard for the Design of High-Performance Green Buildings 189.1–2014 [33] and ASHRAE Standard 90.1 User's Manual [34]. These schedules represent statistically averaged building operational parameters and runtimes for the retail amenities for more realistic and accurate results from the simulation.

Table 1
Complex Design Inputs.

Parameter	Value
Insulation – Retail	Exterior walls & boundary with greenhouse: 3.3 m^2K/W Roof: 5 m^2K/W
Dimensions– Retail	45 m × 35 m x 4.3 m
Dimensions – Coldroom within Retail	30 m × 10 m x 4.3 m
Fenestration area – Retail	0%
Windows – Greenhouse	Triple pane, low–e, argon filled

The following schedules have been defined for weekday, Saturday, Sunday, and holidays for each of the following building energy end-uses as per ASHRAE 189.1 [33]; Alberta Agriculture and Forestry [35] and ASHRAE Standard 90.1 User's Manual [34]:

- Occupancy schedules
- Lighting schedules and runtimes
- Miscellaneous equipment power runtimes and power factors
- Thermostat set-points for summer and winter
- Relative humidity for retail and greenhouse
- HVAC system runtime
- Ventilation schedule
- HVAC fan availability, off-hour operation schedule
- Refrigeration schedule and set-points
- Infiltration schedule
- Greenhouse lighting schedule and lighting controls
- Greenhouse temperature and air-circulation schedule
- Greenhouse CO_2 supply schedule
- Site lighting schedule

Additionally, daylight saving time is integrated in the schedules to account for the operating energy savings due to the change in equipment and lighting runtime.

3.2.2. Building infiltration

Building infiltration load represents a significant portion of building energy use and it is an important consideration for building energy conservation.

The sustainability codes and standards in force in the studied location address building infiltration, with mandatory design features to limit the building infiltration by defining different building envelop design features and enforcing construction best practices [25–27].

For this study, the statistically average infiltration values of 0.2 $L/s/m^2$ of envelope area is used. This amounts to an approximate air change per hour (ACH) rate of 0.05 at 75 Pa for the entire Complex.

3.2.3. Duct leakage

To account for the building energy waste heat attributed to duct leakage, the tightness levels as per the Sheet Metal & Air Conditioning Contractor's National Association [36] have been modelled for this study. The duct leakage is modelled using maximum permitted leakage of 0.05 $L/s/m^2$ of duct surface area at a pressure difference of 0.24 kPa [37].

3.3. Additional buildings inputs

The following sections discuss specific inputs for both retail and greenhouse.

3.3.1. Retail

3.3.1.1. Occupancy rate. Occupancy rate for the retail area is modelled as 0.15 $person/m^2$ as per the ASHRAE 62.1 Standard for Ventilation and Indoor Air Quality [38].

ASHRAE Standard 62.1 applies to all spaces intended for human occupancy except those within single-family houses, multifamily structures of three stories or fewer above grade and is mandated by the governing building code for the project site [25].

3.3.1.2. Ventilation rate. Ventilation rate per person is based on the standard ASHRAE 62.1 [38]. ASHRAE 62.1 [38] prescribes a combined outdoor air rate at 7.8 L/s per person in Table 6.2.2.1 Minimum Ventilation Rates in Breathing Zone of the standard.

To ensure effective zone air distribution of the supply air to maintain acceptable air quality in the occupied zone, ASHRAE 62.1 [38] has defined a parameter called Zone Air Distribution Effectiveness (E_z). E_z determines the air distribution efficiency based on the space and supply

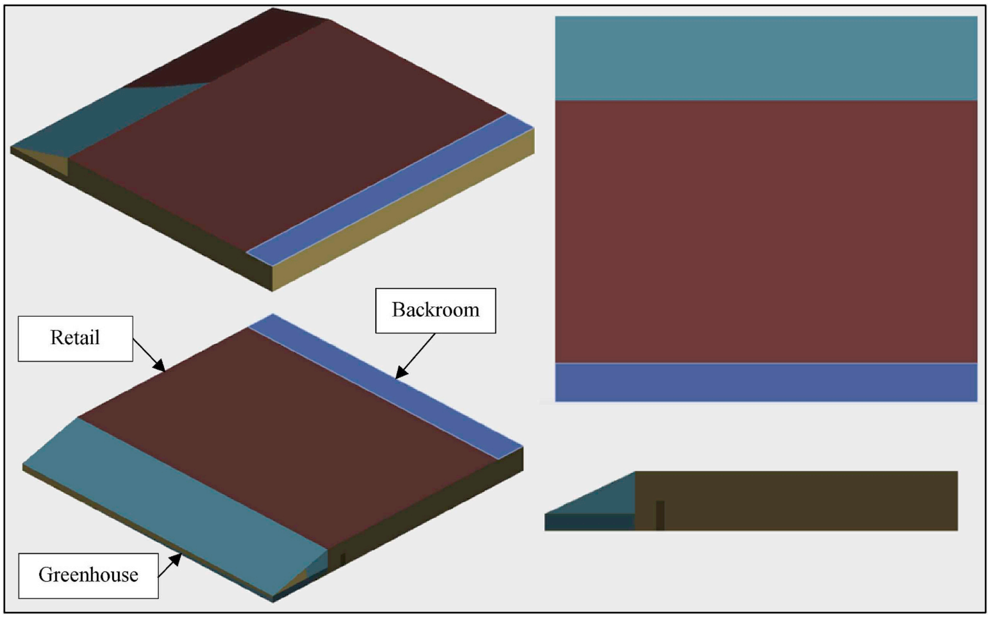

Fig. 1. Geometry of retail-greenhouse complex.

air temperatures and the location of the supply air and return air diffusers, respectively.

For the current study, typical ceiling supply and ceiling return ducts are assumed. E_z air distribution configuration of ceiling supply of warm air 8 °C or more above space temperature and ceiling return has been used. E_z factor for this configuration is 0.8. Equation (1) shows the calculation of ventilation rate per person for retail area:

$$Ventilation_{Retail} = \frac{Ventilation_{\ Breathing\ Zone}}{E_Z} = \frac{7.8}{0.8} = 9.75 \simeq 10\frac{liters}{sec}/person \quad (1)$$

Hence, a ventilation rate of 10 L/s per person has been used for this study for the retail area.

To ensure uniform air distribution and better indoor air quality, the room air model type used for the simulation has been chosen to be 'mixing mode'. The mixing mode of ventilation ensures even quality of the air in the entire volume of the space and avoids any local ventilation dead zones or thermal stratification [31].

3.3.1.3. Service hot water load. Service or domestic hot water (DHW) energy use represents a significant part of building annual energy use. To account for this energy use, the water heating load input into EnergyPlus is based on the average DHW load per occupant of the retail area, as per [39] and NECB [27]. Hot water service heating load of 40 Watts/person is used for the retail area.

3.3.1.4. Lighting. Retail area lighting system is designed based on the lighting power density (LPD) 7.5 W/m^2 as per the Advanced Energy Design Guide for Big Box Retail Buildings, American Society for Heating, Ventilation and Air-Conditioning [7].

Building exterior or site lighting system is defined based on the typical wattage of energy efficient LED lamps, with the total capacity of 2500 W [26].

Interior lighting is modelled to run on schedule of the retail area assuming occupancy sensors [26,27]. Exterior lights are controlled to run on photo-sensors to limit their runtime to the dark hours only.

3.3.1.5. HVAC system inputs. The HVAC system for the Complex is defined akin to the typical industry design practice of using packaged roof-top units for the retail area. This type of HVAC system is suitable for the retail blocks and is the industry practice due to its scalability and ease of maintenance [39]. Electric heating coils and direct expansion (DX) cooling coils are modelled for the HVAC system.

The HVAC system heating and cooling supply air temperatures are modelled based on maximum heat transfer effectiveness and optimal operating cost. Additionally, the supply air set-points are selected to operate above the dew-point temperatures to ensure occupant health and indoor air-quality and avoid mould growth. Hence, the maximum heating supply air temperature is 50 °C and minimum cooling supply air temperature is 13 °C [31].

Based on these supply air temperatures, the retail area winter and summer set points are assumed 22 °C and 25 °C, for Winter and Summer, respectively [26].

3.3.1.6. Electrical equipment and plug load. To account for the retail area equipment, appliance and plug load (e.g. retail area checkouts, computers, display screens, microwaves, re-therm appliances etc.) total plug load of 17 kW is modelled for the entire Complex. Plug load is modelled based on the manufacturer's data for the retail equipment, as derived by Ref. [3].

3.3.1.7. Process load. Refrigeration related process loads are modelled in EnergyPlus. The temperature of the cold room is set from 2 to 5 °C to maintain a safe temperature for the products stored within [3].

Based on the energy management guidelines for the retail food refrigeration and equipment stated in ASHRAE [40]; it has been assumed that the glass doors and air-curtains have been provided on refrigerators and freezers as a barrier against infiltration.

3.3.2. Greenhouse

3.3.2.1. Ventilation/air-circulation requirements. Al-Helal et al. [41] states that although investigation of natural ventilation in the greenhouses started 50 years ago, there is still no adequate method to precisely predict the amount of natural ventilation needed for such structures. For instance, as noted by Ref. [42]; despite several computational fluid dynamics (CFD) optimization models, the necessity of putting insect proof nets at the vents may drastically reduce the efficiency of natural ventilation (up to 50%). Therefore, forced ventilation is becoming a more popular mode of ventilation/cooling and forms an effective mean of alleviating the solar loads and improving the greenhouse climate conditions. Additionally, Nickey

et al. [30] has shown that the natural ventilation alone may result in more energy consumption in certain cases.

Several studies have provided ventilation or air-circulation rates for greenhouses e.g. NGMA [60] and [42]. Kittas et al. [42] has developed a simplified ventilation formula based on extensive experimentation as below, as shown in Equation (2):

$$V_a = \frac{1}{86}\left(\frac{0.026\tau R_{s,o-max}}{\Delta T} - 1\right) \quad (2)$$

Where:

V_a = greenhouse ventilation rate ($m^3/s/m^2$)
ΔT = outside dry bulb temperature – maximum greenhouse temperature
$R_{s,o-max}$ = maximum solar radiation during solar summer, under clear sky (W/m^2)
τ = greenhouse transmissivity to the solar radiation

For very high levels of $R_{s,o-max}$, the formula could be written as below, as shown in Equation (3) [42]:

$$V_a = \left(\frac{0.0003\tau R_{s,o-max}}{\Delta T}\right) \quad (3)$$

Greenhouse ventilation rate formula for climate control, as developed by Ref. [42] has been validated by other experimental studies, for example Benis et al. [43].

Another crucial consideration for mechanically ventilated greenhouses is the requirement of carbon dioxide (CO_2) for the plant growth and crop yield. CO_2 is essential for the plant photosynthesis, which is a process through which plants produce sugar to help in their growth. CO_2 concentration has a major impact on the plant growth and all plants react positively to the CO_2 concentration [44].

Alberta Agriculture and Forestry recommend that for even distribution of CO_2, humidity and temperature in greenhouses, it is important to maintain the following air circulation conditions [35]:

- Fan capacity: 0.9–1.1 m^3/s per square meter of the greenhouse area
- Air velocity < 1 m/s
- Air circulation rate: 0.1 m^3/s

3.3.2.2. Irrigation water thermal treatment. Irrigation water temperature is recommended to be within the range of 18–35 °C. Crop water requirements correspond to the volume of water that a plant needs to maintain maximum rates of evapotranspiration [45,46].

Water temperature for irrigation for greenhouse has been modelled at 18 °C in EnergyPlus.

3.3.2.3. Lighting. Photosynthesis and photo morphogenesis are the two most important plant processes impacted by the light [47]. Approximately 80% of total light falling on the greenhouse reaches the crop at noon, with an overall average of 68% over the day [48].

Photosynthetic Active Radiation (PAR) is a concept used to describe radiation in the wavelengths useful for photosynthesis in the plants. The PAR is accepted to be between 400 and 700 nm. At shorter wavelengths, the photon energy can damage the plants, while at longer wavelengths the energy is insufficient to trigger photosynthesis. This wavelength spectrum is similar to the visible spectrum of human eye. All plants show a peak of light use in the red region, approximately 650 nm and a smaller peak in the region at approximately 450 nm [35].

PAR is also termed as daylight intensity (DLI), expressed in $mol/m^2/day$ as the measurement of photons that reach a plant during the day photoperiod for photosynthesis. Photoperiod is the period of time each day during which natural or artificial light is available to generate photosynthesis.

In order to reach the optimal PAR for the plants especially in the shorter winter days, PAR from the daylight is usually supplemented with artificial light. The magnitude of supplemental PAR is shown in Equation (4) [43]:

$$PAR_{Crop} - PAR_{Daylight} = PAR_{Sup} \quad (4)$$

Where:

PAR_{Crop} = light requirement for optimal growth of the crop ($mol/m^2/day$)
$PAR_{Daylight}$ = available daylight measured at the plant canopy
PAR_{Sup} = supplemental light needed for optimal plant growth

Based on the difference between the optimal PAR of the crop species, and the PAR that is provided by the daylight, the deficit PAR represents the need of supplemental artificial lighting.

AGRIC [48] has shown that for Alberta, the maximum yield occurs for a photoperiod of 16–20 h, while beyond 20 h, the yield starts to decrease. The amount of light varies for each crop but ranges approximately between 120 and 180 W/m^2, coming from a 400 Watt lamp [48]. Hence, LPD for greenhouse has been modelled at an average 150 W/m^2 in EnergyPlus.

3.3.2.4. HVAC system and temperature set-points. Plants tend to grow best under the range of 17–27 °C. The average night time temperature for heat-requiring plants has been suggested as 15–18.5 °C [35,42,43,45,46].

To achieve the required indoor conditions in the greenhouse area, a combination of furnaces and electric terminal unit heaters is assumed due to the prevalence of these systems in the greenhouses per extensive investigations by Elsner et al. [45] and Vanthoor et al. [46], respectively.

4. Optimization of the complex

Simulations are conducted for the base model developed as per the details presented in section 3. Energy performance in terms of heating, cooling and various other loads are estimated on a yearly basis. Numerous innovative technologies and high-energy efficiency measures (ELM), are modelled in EnergyPlus to optimize the performance of Complex. Details are presented below:

4.1. Energy efficiency measures

4.1.1. HVAC air-side economizer

HVAC air-side economizer uses outdoor air to cool the space when possible. When the temperature of outside air is less than the indoor air and there is cooling load, the outside cooler air can be brought in the building without using the mechanical cooling. This can result in significant energy savings by reducing the reliance on the mechanical cooling (DX or chillerst etc.) during the shoulder seasons.

The HVAC air-side economizers have been modelled in EnergyPlus. Based on the typical design practice, the compressor lockout temperature set at 20 °C is used.

4.1.2. Heat recovery ventilation

Heat from exhaust air leaving the HVAC units can be recovered to heat the fresh outdoor air entering the HVAC units. There are several types of heat recovery systems available with varying effectiveness and design/operational complexities. Some examples include heat recovery wheel, plate and frame heat exchanger, run-around loop, heat pipes etc. The effective heat recovery efficiencies of these systems typically vary from 45 to 90%.

Typical heat recovery ventilation systems used for the small to medium scale HVAC units are heat wheels. Heat wheels are rotary disks that pick heat from the exhaust air and transfer that heat to the incoming outdoor air.

Because of the northerly Canadian winters, there is a chance of frosting on these heat wheels during colder temperatures. Therefore, a heat wheel de-frost mechanism is installed. With the de-frost cycle, the net heat recovery effectiveness for these wheels is approximately around 0.65 (i.e. 65%).

Heat recovery ventilation employing the heat wheel concept has been modelled in EnergyPlus.

4.1.3. Optimizing appliance and plug loads

Appliances or plug loads (excluding process loads, e.g. commercial refrigeration, commercial cooking etc.) can amount to a significant energy use in a typical building. As per LEED [49]; it is not uncommon for some building to have appliance and plug loads as high as 25% of the total building use. The appliance and plug loads have direct impact on the building heating and cooling loads as well.

Plug loads for the retail area are based on ASHRAE Standard for the Design of High-Performance Green Buildings 189.1 [40]. This amount to the appliance/plug load equivalent to 2.7 W/m^2 for the retail [40].

4.1.4. Lighting optimization

Interior lighting can offer significant energy saving potential. One of the most common way to optimize the building interior lighting is the effective use of automatic lighting control. Most common lighting control methods are occupancy sensors (on/off control), day lighting sensors (on/off control) or dimming controls (multi-step or continuous dimming) based on the available natural light.

The lighting controls have been modelled in EnergyPlus by reducing the effective lighting power density as per ASHRAE Standard 90.1 [26].

Exterior site lighting has been modified to run till the mid-night and then switch to turning off every alternate exterior lamp. This schedule is applied to maximize energy savings without compromising the site security and safety.

4.1.5. Process refrigeration compressor optimization

Refrigeration (including walk-in freezers and walk-in coolers) relies on the thermodynamic vapour-compression cycle for generating low temperatures. As a result, a significant mechanical energy input to the compressors is required to create the cooling effect. Process cooling in the retail areas can be a significant source of energy use but offers several practical opportunities to implement energy saving measures as well.

Based on the requirement in the Standard for Performance Rating of Walk-in Coolers and Freezers by the Air-conditioning, Heating and Refrigeration Institute (AHRI) Standard 1251 [50], the process refrigeration compressor systems have been modified to an increased performance level. Hence, new multi-stage compressors with magnetic bearings have been modelled in EnergyPlus, with the nominal coefficient of performance of 4.5. The coefficient of performance or COP of refrigerator or air conditioning system is a ratio of useful heating or cooling provided to work required. Higher COP equates to lower operating costs [50].

Significant energy savings result with this modification. Such high performance process refrigeration units are commonly used in the commercial retail sector due to their lower energy footprint.

4.1.6. Refrigeration air-cooled condenser optimization

Compressor rack rejects heat to air in the current model. This heat rejection consists of circulating air over the heat rejection coils of the condensers through a fan. This rejected heat can be recovered and used in the building mechanical system.

However, the foremost energy efficiency strategy is to minimize the fan energy usage in the air-cooled condensers by reducing the energy wastage from the refrigeration cycle and employing efficient fan and motor designs. That is obtained through a variety of measures including, but not limited to, condenser fan optimization through variable frequency drives (VFD), building management system (BMS) optimization or improving the compressor COP [51,52].

For this study, the choice of implementing the VFDs in the condenser fans is used.

4.1.7. Water conserving service hot water faucets

To conserve energy used to heat the service hot water of the Complex, low-flow faucets have been modelled in EnergyPlus. The low flow faucets with a rating of 1.9 L/min flow are chosen. The resulting reduction in the service hot water usage is modelled in using the design tool provided by the Canada Green Building Council (CaGBC) templates for the [49,53]. CaGBC [53] uses an excel based template to calculate hot water consumption based on the typical usage and occupancy of a building and the type of plumbing faucets used.

4.1.8. Hands free controls for service hot water faucets

Studies have shown that the use of automatic, hands-free faucet controls can reduce the service hot water usage significantly [49]. Based on the average 15 s runtime of automatic faucets vs. approximately 60 s average runtime for the hand washing sinks, there is a significant potential for the reduction in the hot water use.

A conservative 30% reduced service hot water load has been assumed for this ECM, following the design guidelines of innovative wastewater technologies per LEED [49].

4.1.9. Waste heat recovery from compressor racks

Retail floor area is operating refrigeration systems continuously to maintain proper food storage conditions within their refrigerated display cases and storage areas. The waste heat recovered from a commercial refrigeration system typically consists of either only the heat which is required to de-superheat the compressor discharge gas, or both the heat required to de-superheat the discharge gas as well as the heat required to condense the refrigerant from a saturated vapour to a saturated liquid. The waste heat from the former is known as de-superheating waste heat while that from the latter is known as full condensing waste heat. Generally less waste heat is recovered through only de-superheating as compared to full condensing, however the quality of the heat recovered by only de-superheating is higher, i.e., the temperature of the waste heat from de-superheating is higher than that obtained from full condensing [5].

Waste heat from compressor racks is recovered and shared between the greenhouse and retail areas, respectively to meet the heating needs of these spaces. Energy sharing strategy and results are discussed in section 5 of this paper.

4.2. On-site solar photovoltaic energy generation

Solar photovoltaic (PV) system is modelled to achieve net-zero design. A net-zero building produces as much energy as it uses over the course of a year. In the case of the Complex design, it is assumed to have a two-way electric utility meter to import the electricity when the renewable energy systems are not able to meet the demand and export energy to the utility grid when excess generation occurs in the real-time.

The PV system for the Complex is modelled in EnergyPlus. Crystalline Silicon PV cells with fixed tilt of 45° are modelled with system efficiency of 15%.

Based on sensitivity analysis with different PV system capacities, it has been found that to achieve an annual net-zero site energy 360 kW capacity is needed. PV system capacity is expected to generate approximately 2200 GJ or 610 MWh of electrical energy to meet the total annual energy requirement of the Complex.

Approximate roof area required for the installation of 1 kW solar PV system is found to be approximately 10 m^2 based on preliminary estimates from SolarRoof [54,55] and Alberta Infrastructure [56]. While it is understood that the solar PV system potential varies on the system performance parameters, site orientation and location, a detailed PV

system analysis is outside the scope of the current study.

Based on the gross roof area of the retail, approximately 1500 m^2 of the roof area is available for the PV systems. Other mechanical and building systems e.g. exhaust fans, roof-top HVAC units, code mandated plumbing drains and gas lines etc. require certain levels of clearances and dedicated area [25]. Therefore, in addition to 1500 m^2 area on Complex roof, approximately 2100 m^2 of adjacent land area is needed to install PV plant for the Complex.

4.3. Energy sharing within the complex

A multiuse complex design can be optimized to harness on-site energy and sharing energy between the individual buildings to reduce dependence on utility grid. This study explores the concept of energy sharing between greenhouse and retail including electricity and heat with an aim at reducing dependence on utility grid. Energy sharing aims to enlarge the usage of unused energy effectively with an increase in the potential of energy utilization that will be wasted otherwise. For example, heat generated by refrigerators in the retail instead of beign rejected to the environment can be used to heat the greenhouse.

Waste heat recovered from the compressor rack is used for irrigation water heating, ventilation air heating and space heating for the greenhouse. The remainder heat from the compressor rack is used to heat the retail floor. The deficit heat supply is provided by HVAC system, comprising of air heating furnaces.

An air to air heat exchanger is assumed to recover the waste heat from the compressor rack. The waste heat is shared with the greenhouse by transferring this heat to the heating coil of the for the greenhouse furnace. In addition, an air to water heat exchanger is modelled to recover compressor rack waste heat and transfer to the DHW coils to heat the irrigation water for the greenhouse.

Energy flow and energy sharing schematics for the Complex are shown in Fig. 2. The heating energy recovered from compressor rack in the backroom is available for sharing between the greenhouse and retail area.

As shown in Fig. 2, the waste heat is recovered from the Backroom where retail refrigeration condensing unit is located. The recovered heat (H_{share}) is transferred to an air loop that is connected to the furnaces serving the Sales Floor and Greenhouse. In addition H_{share} is shared between the Backroom and Greenhouse to heat irrigation water for the plants. Since no heat storage system is analysed for this study, heat recovered from the compressor rack that is not used in the real time is discharged to the atmosphere ($H_{exhasut}$).

For electric energy, a balance between demand and production is calculated for every hour and surplus is exported to grid, while any deficit is imported. Renewable electricity generated on site is shared (E_{share}) within the Complex. E_{share} is used to meet the following loads of individual buildings in the Complex:

- Plug loads
- Refrigeration load
- Lighting
- Space cooling
- DHW heating
- Ventilation fans

Renewable electricity not used on site is exported back to the utility (E_{export}).

The design concept and schematic of energy sharing developed in this study can be generalized and applied to a wide range of building sizes and combinations.

Energy sharing between the individual buildings of the Complex can be formulated as shown in Equation (5). Equation (5) shows that at any given point the amount of energy shared between the two structures (greenhouse and retail) of the Complex is equal to the net balance of energy. Hence, at a given point in time, the amount of energy shared between the individual buildings of Complex is equal to the difference between the surplus energy in the Complex boundary and the deficit of energy for the individual buildings in the Complex.

$$Energy_{Share} = min\left[\sum Energy_{Surplus}, \sum Energy_{Deficit}\right] \tag{5}$$

Energy supply from the neighbouring building is available in energy sharing cases as shared amount of electricity (E_{share}) and heat (H_{share}).

The amount of shared energy at each time of day can be calculated according to the net balance in the total E_{share} and the total H_{share} of all buildings within the Complex. Surplus electricity, which is not utilised completely within the Complex, is exported to the utility grid (E_{export}). The excess heat after sharing is released into the air ($H_{exhaust}$).

5. Results and discussion

5.1. Code compliant model

Table 2 presents the results of code compliant base models. Cooling presented in Table 2 is only the envelope related cooling energy usage and not the refrigeration energy usage. The Miscellaneous items contain the following building energy end uses:

- Refrigeration energy use
- hot water load
- store signage
- Roof de-stratification fans
- Snow-melt system for main entrance
- HVAC fans
- Plug and appliance loads

The energy breakdown is also presented in Fig. 3 below. Fig. 3 shows that for the base case design, heating constitutes 35% of annual energy, cooling 1%, interior lighting 8%, exterior/site lighting 1% and plug loads/miscellaneous loads constitute 23% of the total site load. In addition, refrigeration constitutes 32% of annual site energy.

The energy breakdown between the individual buildings of the Complex is as follows:

- Retail Annual Energy: 86%
- Greenhouse Annual Energy: 14%

The daily energy usage profile for the complex is shown in Fig. 4 below. Fig. 4 shows the total heating load (including space heating, ventilation air heating and service hot water heating) for Complex. Similarly, cooling energy use profile includes space cooling, ventilation air cooling for Complex.

5.2. Validation of code compliant model

The results of the EnergyPlus base case model is validated as per below.

5.2.1. Energy density benchmarking validation

The energy density results of the retail section of the Complex have been validated against the comprehensive energy use database for the commercial and institutional sector in Alberta, as provided by the Natural Resources Canada [57]. This database contains most up to date, statistically averaged summary of the energy and GHG data provided by the Office of Energy Efficiency of the Government of Canada. The benchmarking data for the secondary energy use for the 'Retail Trade' sector is used for realistic comparison. This benchmarking database has been derived from the statistical averages of the available energy end use information from the years of 1990–2015, thus offering a high statistical confidence interval of the accuracy of the energy benchmarking data.

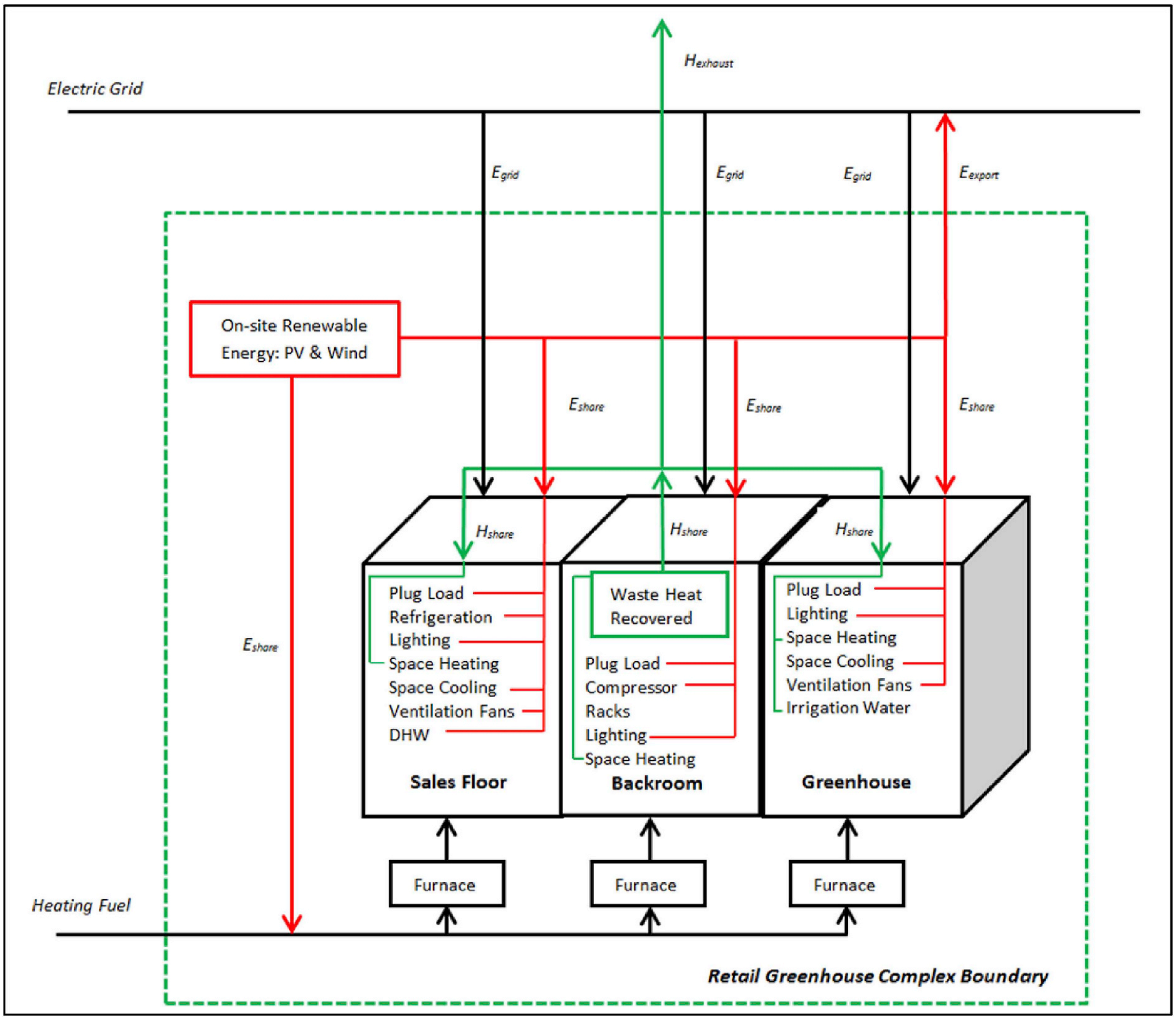

Fig. 2. Energy flow and sharing schematic.

Table 2
Annual energy use of complex.

Parameter	Annual Site Energy	Energy Density
Total Site Energy	3070 GJ (850 MWh)	1.47 GJ/m^2 (410 kWh/m^2)
Building Energy	**Annual Energy**	**Energy Density**
Greenhouse	**430 GJ (120 MWh)**	0.95 GJ/m^2 (264 kWh/m^2)
Retail	**2570 GJ (730 MWh)**	1.63 GJ/m^2 (453 kWh/m^2)
End Uses	Value	Percentage
Heating	1080 GJ (300 MWh)	35%
Cooling	19 GJ (5 MWh)	~1%
Interior Lighting	237 GJ (66 MWh)	8%
Exterior Lighting	39 GJ (11 MWh)	1%
Miscellaneous	707 GJ (196 MWh)	23%
Refrigeration	990 GJ (275 MWh)	32%

Twenty five year average energy density of the typical retail trade area in Alberta is 1.83 GJ/m^2 or 508 kWh/m^2 [57].

Ampong-Nyarko [58] provides comprehensive energy use benchmarks for Alberta greenhouses and the approximate value for a statistically average greenhouse energy use for the project site is 2.94 GJ/m^2 (816 kWh/m^2).

The area weighted average energy density for the Complex is presented in Table 3 and Equation (5) below:

Equation (6) show the area weighted average energy density of the Complex, based on the energy benchmarking data presented in Table 3.

$$\text{Complex Energy Density} = \frac{1.83 * 1630 + 2.94 * 457}{1630 + 457} = 2.07\frac{GJ}{m^2} = 575\ kWh/m^2 \tag{6}$$

The site energy density of the Complex is 1.47 GJ/m^2 (408 kWh/m^2) compared to a province wide, area weighted average of 2.07 GJ/m^2 (575 kWh/m^2) as shown in Equation (6). The base case has shown approximately 28% improvement in its performance compared to the base case reference model in the studied location. This variation can be attributed to the improved envelope, mechanical, plumbing, electrical and lighting performance requirements mandated by the incumbent building and sustainability codes in Alberta, Canada.

5.2.2. Energy use breakdown validation

Energy end use breakdown as predicted by EnergyPlus has been validated by running an independent energy model in the EE4 [59]. EE4 is a DOE based energy use assessment tool developed by the Natural Resources Canada for validation of new building designs.

The refrigeration related energy use, being a process load, is modelled as a plug load in the EE4. The simulation results and the energy breakdown have been compared against EnergyPlus and have been found to be in general agreement.

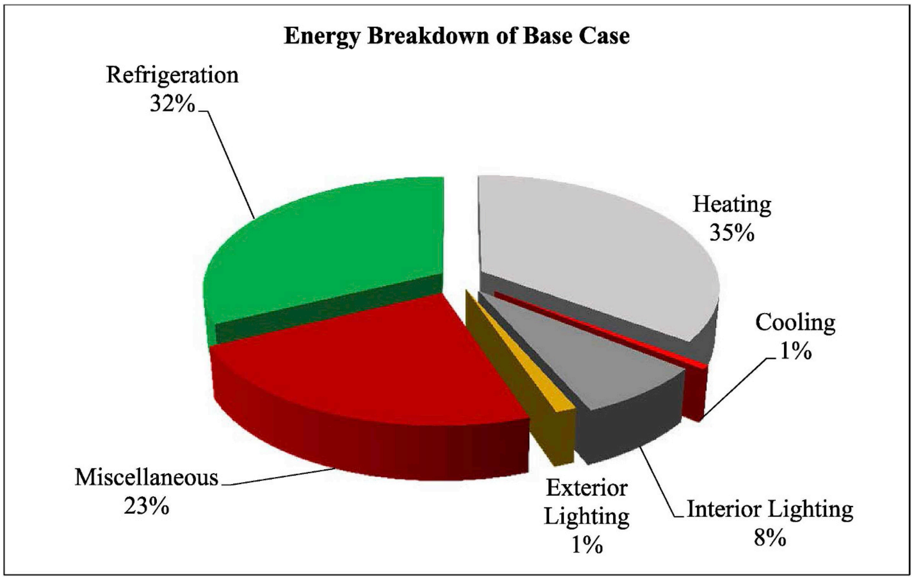

Fig. 3. Energy breakdown of base case.

5.3. Results of optimized complex model

Table 4 shows energy performance with the optimization strategies modelled for the Complex. Results show that with optimization strategies and waste heat recovery, there is a net 27% reduction in the energy usage of the Complex compared to the code compliant base case

Table 3
Energy benchmarking data for retail and greenhouse.

Building	Energy density (GJ/m^2)	Area (m^2)
Retail	1.83	1630
Greenhouse	2.94	457

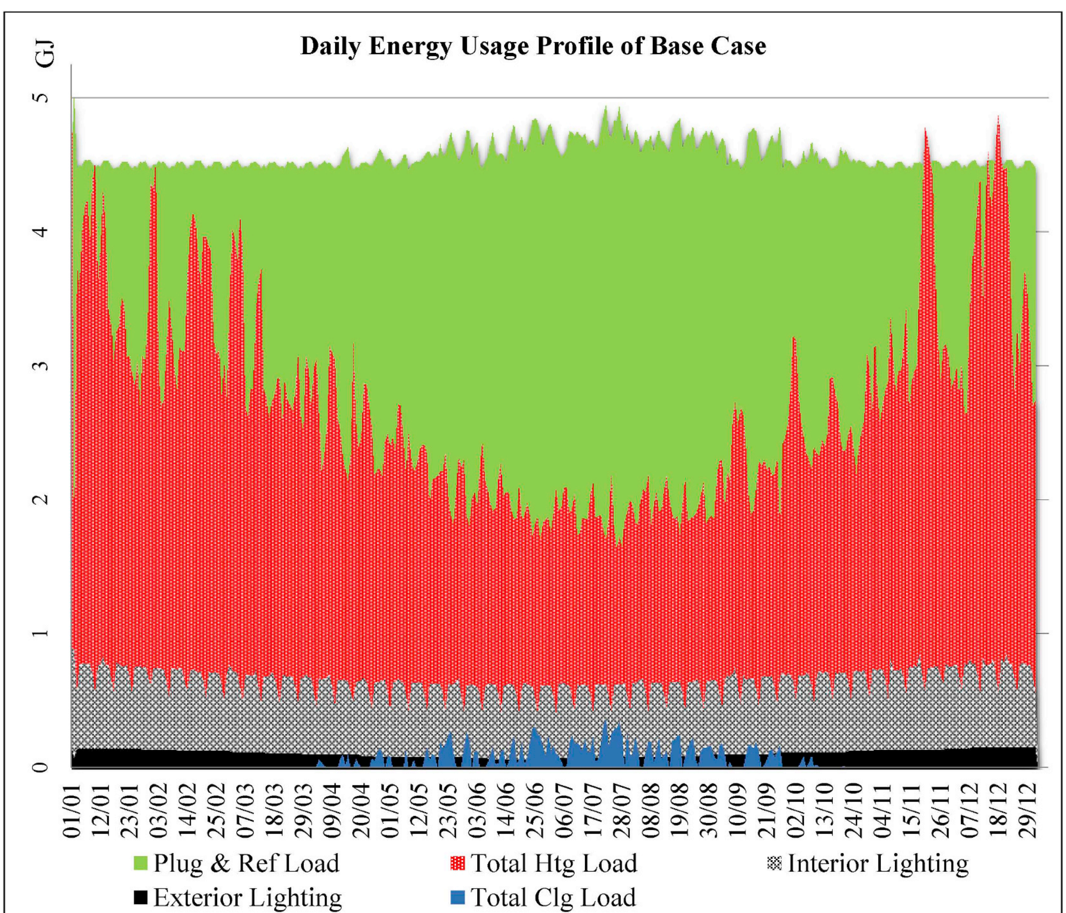

Fig. 4. Daily energy usage profile of complex.

Table 4
Optimization with ELM.

Parameter	Annual Site Energy	Energy Density
Total Site Energy	2200 GI (610 Mwah)	1.06 GI/m^e (290 kWh/m^e)
Scenarios	**Analysis**	
Code Compliant	3070 GI (853 Mwah)	
Improved Design	2200 GI (610 Mwah)	
Energy Saved	27%	

design.

Energy usage profile with the optimized design and waste heat recovery from the compressor rack is shown in Fig. 6. Fig. 6 shows a significant reduction in plug and refrigeration energy usage. This is attributed to optimization of plug loads of Complex by using efficiency and high COP refrigeration system for process cooling in the retail area and optimization of air-cooled condenser and modelling VFD for the condenser fans.

Fig. 5 shows a net increase in heating energy usage and that is attributed to reduction in plug loads and optimization of refrigeration equipment. Appliance and plug load heat rejection will impact the air heat balance in this zone [31]. Since the appliances and plug loads are using less energy and consequentially lesser waste heat is available to the zones, there is a net increase in the heating energy of Complex. However, despite a net increase in heating energy of the Complex, there is a net reduction of 27% in the total site energy, as shown in Table 4.

Fig. 6 shows the breakdown of energy use in the greenhouse. It can be seen that during summer the cooling energy use increases and lighting energy decreases due to longer sunshine hours. Similarly, heating load follows the dry-bulb temperature. The heating energy usage increases in cooler months due to the energy required to heat the greenhouse.

5.4. On-site renewable energy and electricity management for the complex

On-site electricity is generated to provide net-zero energy for the Complex. PV energy is diurnal in nature and over 8760 h of a year when energy is surplus and is not utilised completely within the energy community, is exported to the utility grid. Similarly, when there is a net deficit the electrical energy is imported from the utility grid. A total of 2200 GJ or 610 MWh electricity is generated on site by the PV system.

The result of building energy usage and the on-site energy generated is shown in Fig. 7.

The result of building energy usage and the on-site energy generated is shown in Fig. 8. Fig. 8 shows that during the spring and summer months the on-site energy generation peaks and excess energy is sold to grid. However, during the late fall and winter months, energy needs to be imported from grid.

Table 5 summarizes the percentage of on-site renewable energy generated vs. the site electricity usage on monthly basis.

Fig. 9 shows the energy use in the Complex in comparison to the energy generated on site through PV system. As it can be seen that during summer months when there is more solar energy available, there is a net export of the surplus energy. However, during the fall and winter months, there is a net deficit in the site energy and hence the balance energy is needed to be imported from utility grid.

5.5. Thermal energy sharing in the complex

Fig. 10 represents a Sankey diagram demonstrating the energy flow between the recovered compressor rejected heat that is shared with the adjacent greenhouse.

A total of 130 MWh (470 GJ) of waste heat is recovered from the retail compressor rack. Since no thermal energy is stored on site, the waste heat recovered can only be share within the Complex in the real time.

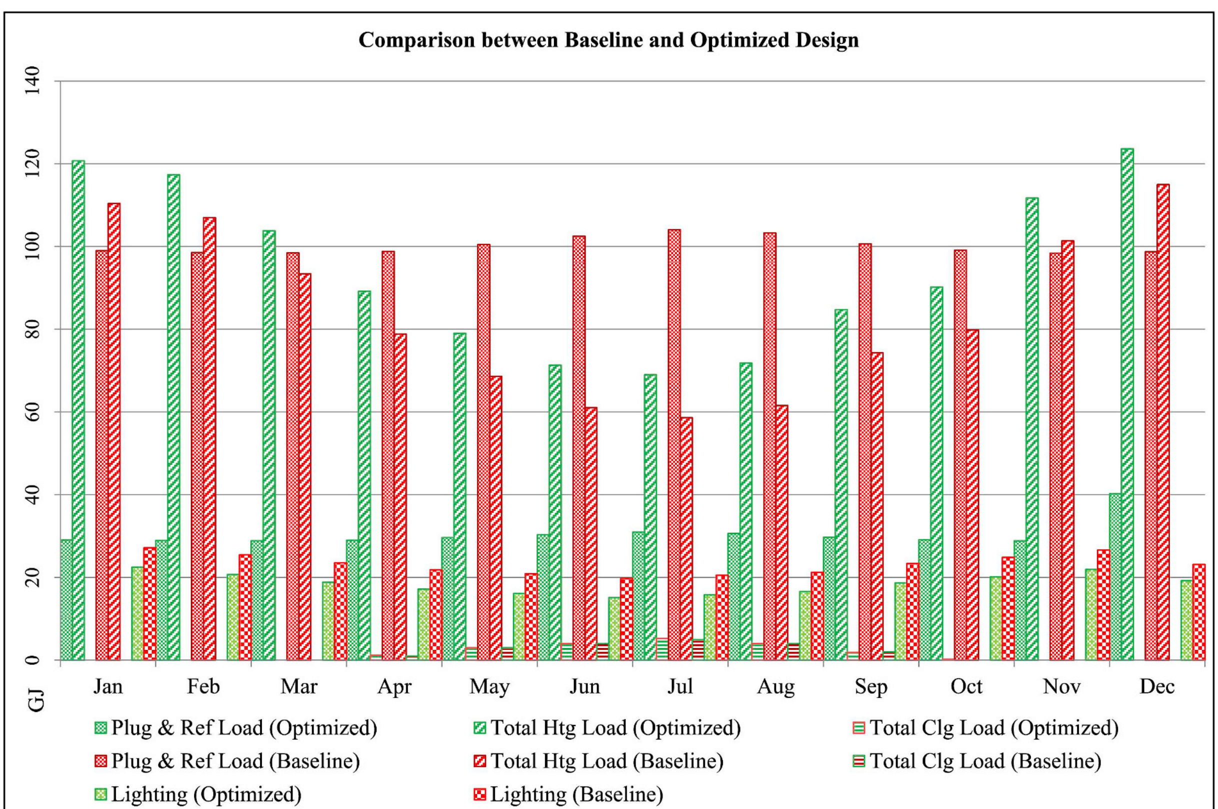

Fig. 5. Comparison between baseline and optimized design.

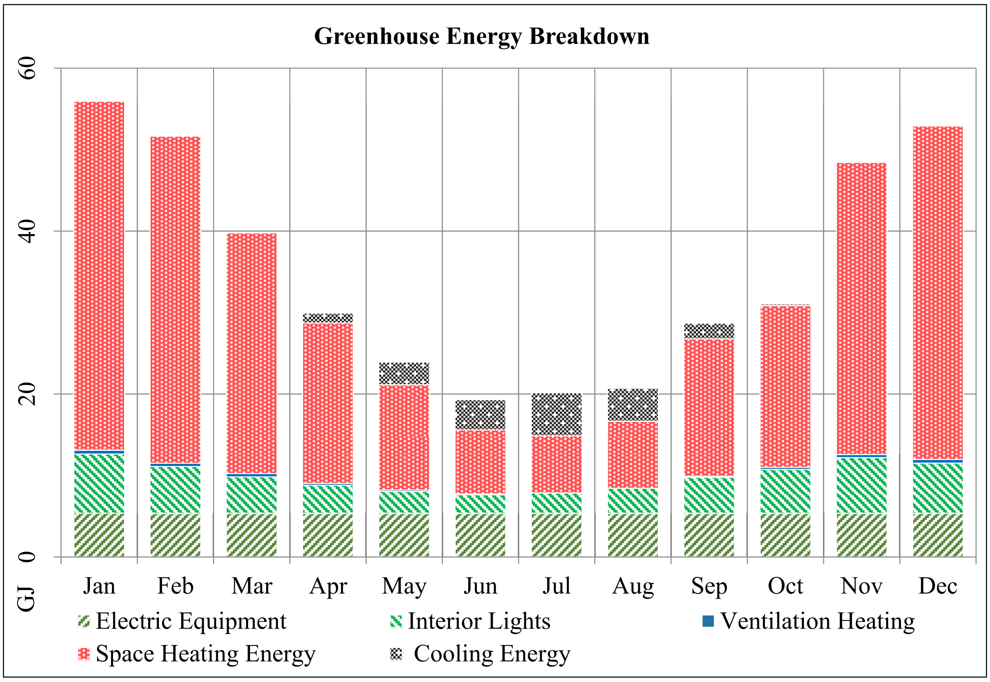

Fig. 6. Greenhouse energy breakdown.

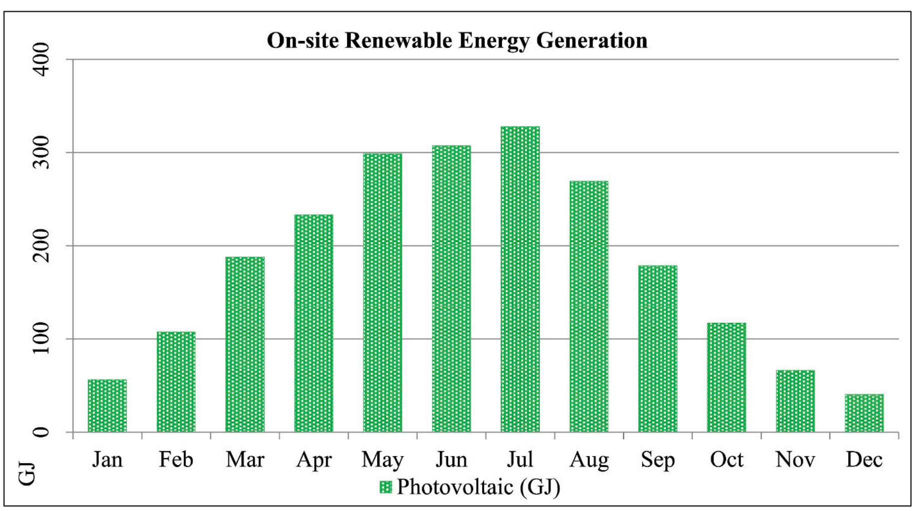

Fig. 7. On-site renewable energy generation.

Fig. 11 shows the monthly heating energy sharing between the retail and greenhouse. Heat captured from the compressor rack is shared with the greenhouse to provide space heating, irrigation water heating and ventilation air heating for the greenhouse.

The remainder of the heat is shared with the retail area to contribute to space heating, hot water heating and ventilation heating energy, respectively. Results analysis has shown that approximately 284 GJ (77 MWh) of waste heat has been recovered from the compressor rack to preheat the HVAC supply air and irrigation water to the greenhouse and retail area, respectively. The recovered waste heat amounts to approximately 21% of the entire heating energy of the Complex on an annual basis.

As a part of future study, more diverse building types including housing sector and standalone urban centric greenhouses will be assessed. A broader optimization of the building sizes, central renewable energy farms and central energy sharing plant will be studied with deeper greening measures and exploring net positive energy communities.

6. Discussion

Findings of this study address gaps in the existing research concerning design options of retail and greenhouses and demonstrate innovative approach to achieve high-energy performance. A building complex is designed to include a food retail building and an attached greenhouse. The retail-greenhouse complex's architectural, electrical, heating, ventilation, air-conditioning and refrigeration system is modelled, using EnergyPlus, for Calgary (Canada).

The main findings of this study are discussed in the following:

A base model is developed to meet the minimum requirements of the building and energy codes. The code compliant reference model of retail-greenhouse complex results in an energy density of approximately 1.47 GJ/m^2 (408 kWh/m^2). The energy density results of the retail section of the Complex have been validated against the comprehensive energy use database for the commercial and institutional sector in Alberta, as provided by the Natural Resources Canada.

Various energy conservation measures are explored for the retail-

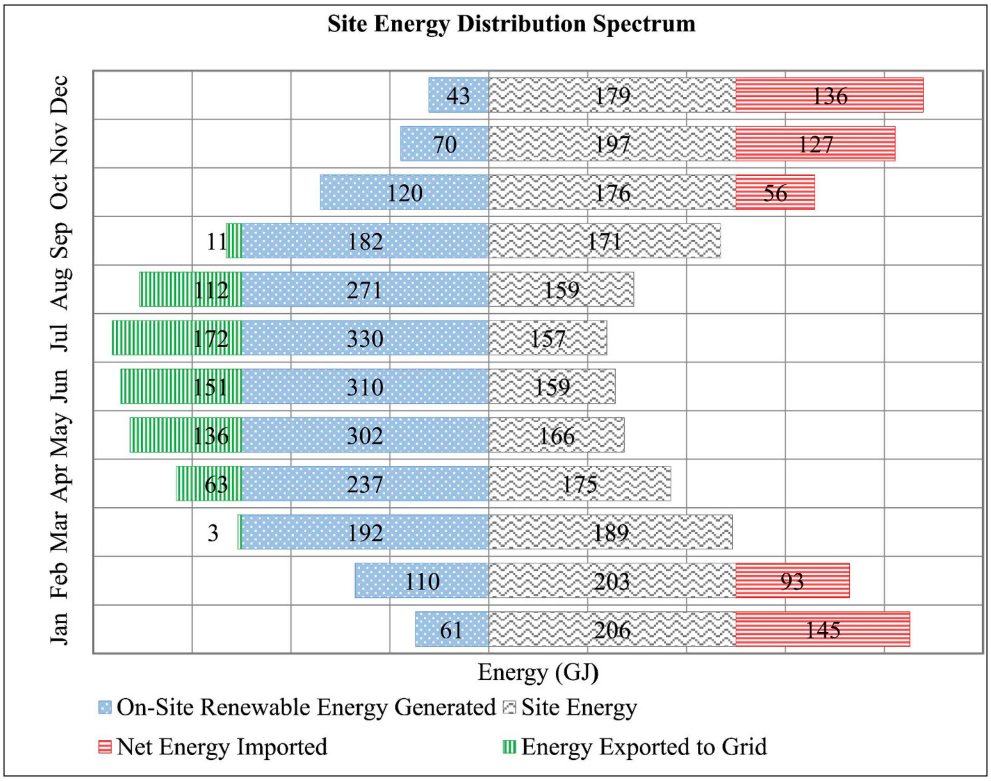

Fig. 8. Building Energy Use vs. On-site Energy Generation.

Table 5
On-site electricity generation vs. Site consumption.

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
28%	53%	100%	136%	181%	194%	208%	169%	106%	67%	34%	23%

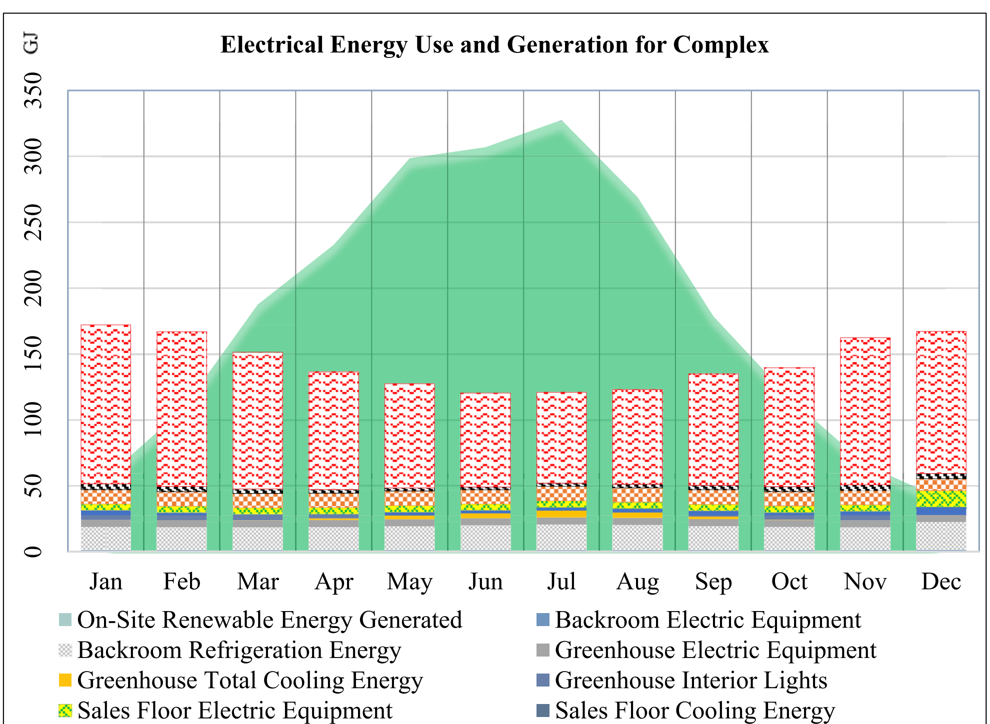

Fig. 9. Electrical Energy Use and Generation for the site.

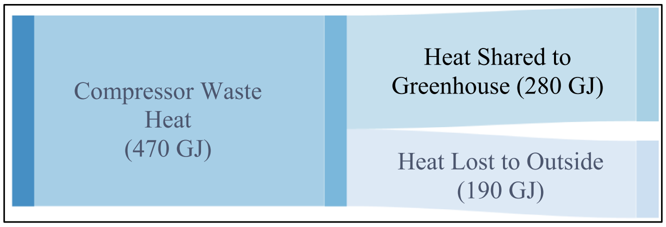

Fig. 10. Sankey diagram of energy flow.

greenhouse complex to reduce the overall energy consumption. Such measures include HVAC air-side economizers, heat recovery ventilation, optimizing appliances and plug loads, optimizing lighting power density, optimizing lighting schedules, process refrigeration compressor optimization, refrigeration condenser optimization, water conserving plumbing faucets and plumbing controls. By implementing these high energy efficiency measures, the energy density of the retail-greenhouse complex has been reduced by further 27% to a value of 1.06 G/m^2 (294 kWh/m^2). This amounts to approximately 49% improvement over the Alberta wide area weighted average energy density of 2.07 GJ/m^2 (575 kWh/m^2).

In addition, energy sharing potential between retail and greenhouse has been explored to further reduce the energy footprint of the retail-greenhouse complex. Waste heat from refrigeration compressor racks is recovered and transferred to the air-furnaces employed to heat the greenhouse and retail area. Runaround heat recovery loop is assumed to recover the waste heat from the compressor rack. The waste heat is shared with the greenhouse by transferring this heat to the heating coil of the for the greenhouse furnace. In addition, an air to water heat exchanger is modelled to recover compressor rack waste heat and transfer to the DHW coils to heat the irrigation water for the greenhouse.

The compressor rack waste heat helps to offset load on the HVAC systems by reusing the energy otherwise rejected to outside. Surplus waste heat from refrigeration compressor rack is shared with the greenhouse, reducing primary energy consumption of the greenhouse in particular and the retail in general. This waste heat sharing has resulted in 21% reduction in the heating energy of the retail-greenhouse complex. The comparison of energy flow from utility has shown that energy sharing within the retail and greenhouse can result in significant energy usage reduction compared to treating buildings separately.

Energy flow schematic has been developed for the Complex. The design concept and schematic of energy sharing developed in this study can be generalized and applied to a wide range of building sizes and combinations. The energy sharing formulation is scalable and can be applied to a variety of buildings and energy system combinations.

Net zero energy design for the Complex has been achieved by an additional 2200 GJ or 610 MWh of on-site electrical electricity generation by solar PV arrays. Excess energy which is not utilised within the retail-greenhouse complex is exported to utility grid. Similarly, when there is a net deficit the electrical energy is imported from the utility grid.

It has been found that by feasible combination of buildings optimized to harness on-site energy and sharing energy between the individual buildings, dependence on utility grids can be reduced, in for climate change resilient urban infrastructure.

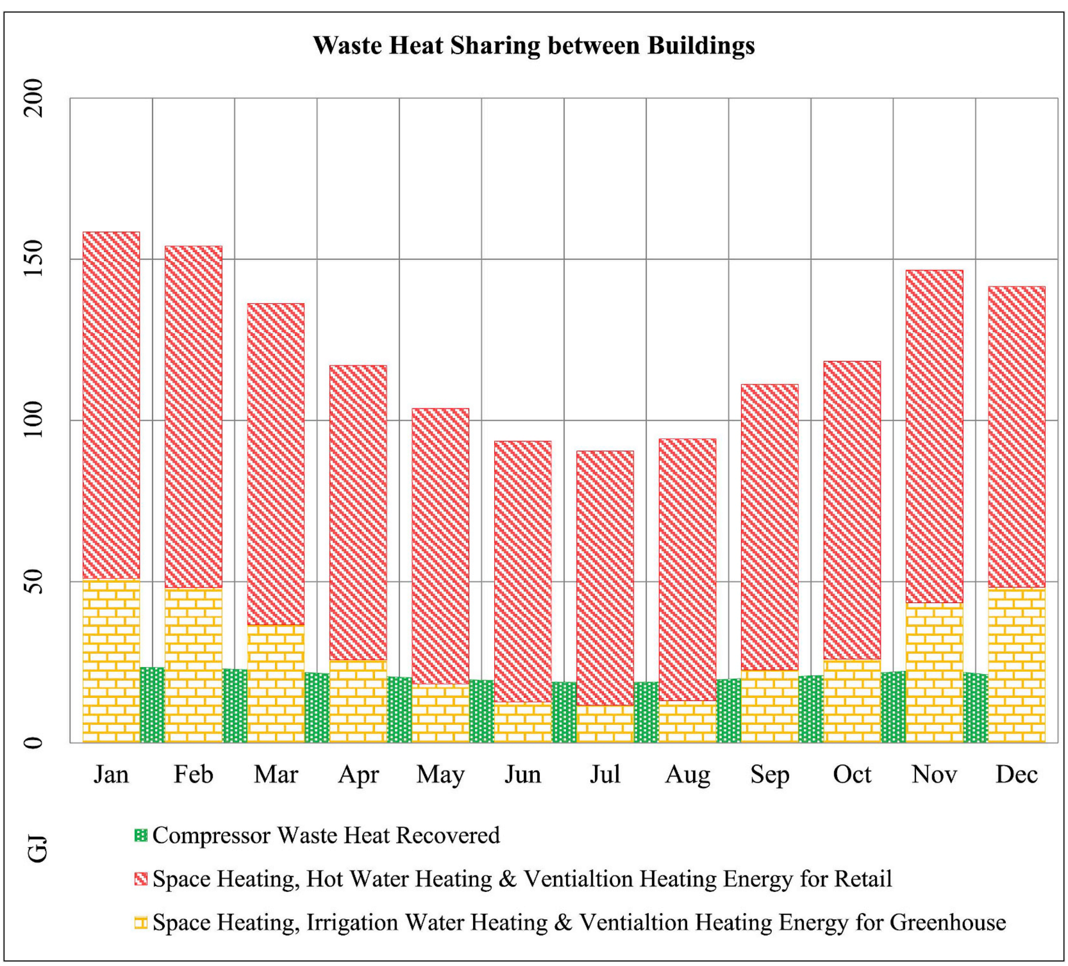

Fig. 11. Energy sharing of recovered heat from compressor rack.

7. Concluding remarks

This paper aims at exploring optimal design parameters, integrating renewable energy technologies and exploring energy sharing strategies for a building complex consisting of an urban centric retail coupled with a greenhouse. The study shows that implementation of energy efficiency measures and innovative technologies leads to a significant improvement in the energy consumption of the building complex. Devising methods to recover waste heat and to utilize it in heating the complex, and specifically the greenhouse, can reduce the overall energy consumption compared to similar buildings. Adding onsite solar PV system can achieve net-zero energy design for the retail-greenhouse complex.

The study shows that implementation of energy efficiency measures and innovative technologies leads to a significant improvement in the energy consumption of the building complex. Devising methods to recover waste heat and to utilize it in heating the complex, and specifically the greenhouse, can reduce the overall energy consumption by 49% as compared to similar existing buildings. Adding onsite solar PV system can achieve net-zero energy design for the retail-greenhouse complex.

This paper presents an innovative and holistic approach on exploring optimal design parameters, integrating renewable energy technologies and exploring energy sharing strategies for a building complex consisting of an urban centric retail coupled with a greenhouse. This approach accounts for combined effects and synergistic impacts and interactions of all the optimization strategies.

Although this study relates to a specific location and presents a prototypical template for coupling greenhouse to a commercial building in a colder, northerly climate, the methodology can be applied for evaluating energy efficient design and optimization of urban centric developments in any other location. This study provides useful information for the architectural and engineering design process for retail sector and greenhouse and the findings can be applied to both new and existing infrastructure. The energy sharing schematics developed for this study can be applied to a wide variety of buildings, HVAC systems, renewable energy systems and energy sharing combinations.

Acknowledgement

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